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**TOMOGRAPHIC OCEAN IMAGING FACILITY:  
2D AND 3D VISUALIZATION OF REAL MARINE STRUCTURES**

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**OBJECTIVES**

The overall goal of this project was to develop an imaging facility which would assist multiple areas of research that depend upon high resolution imaging and, in particular, to develop new approaches to structurally based marine research questions. Research projects relevant to recent Navy needs that would be assisted with the imaging tools in this facility include marine mammal health, diving physiology, marine sensory system modeling, environmental monitoring, documenting the effects of climate change and sound on marine organisms, and three-dimensional modeling of marine structural variations, both organic and inorganic.

This grant provided funds to assist with the purchase and installation of a computerized tomographic (CT) scanner that is fundamental to the establishment of a marine research imaging center at WHOI. The purchased scanner is capable of imaging structures with densities from air through metals at 100 micron voxel resolution and 1 m/min. data acquisition. Installing this scanner at WHOI created a unique, state of the art imaging and visualization center for the marine research community. Contracts to the PI and colleagues that will benefit directly from a scanner are funded by ONR Science-Technology Division/Biosystems Science and Technology Program/Marine Mammal Program and by Ocean, Atmosphere, and Space Science and Technology. Future research related to CT technology and imaging developments will also benefit ONR Medical Science Image Analysis Programs.

**APPROACH**

CT scanning is an invaluable tool for understanding internal structure. Two-dimensional and three-dimensional visualizations of internal structure have proven value for research areas as

diverse as acoustic scattering models, core analyses, and biomimetic sonar models. Rapid, detailed images of internal features can enhance any research requiring structural information but access to existing clinical high-resolution scanners is limited by cost and availability.

Medical CT imaging was established nearly 50 years ago. In the last decade, CT applications were extended to industry but research use is still limited, primarily because of high costs for scan time at clinical and commercial facilities coupled with high demand for the limited time available. Since its theoretical inception in the mid 1940's and the practical demonstration by Ambrose and Hounsfield of tomographic X-ray scanning in the early 1970's, computerized tomography (CT) has revolutionized our ability to understand internal structure of both living tissue and inanimate objects. In the last 10 years, the capacity of CT scanners to provide internal detail took a second major leap with the advent of helical clinical scanning and ultra-fast ceramic detectors. With this technology, it is possible to acquire for objects up to 1 meter in diameter X-ray attenuation data at acquisition densities that yield 20 line pair resolution at speeds of <1 cm/sec. In addition, X-ray attenuations can be measured with up to 40,000 gradations or Hounsfield units. Consequently, tissues or substances ranging from air to soft metals can be differentiated based on attenuations at a 0.1 mm voxel resolution; i.e., imaged at the level of 100 micron cubes.

In practical terms, this means internal differences in structure of a 300-400 lb, 6 foot dolphin can be acquired in less than 3 minutes and then imaged at 100 micron intervals for its entire body. It also means that differences in mineralization in cores, internal structure of fossils, entrapped air and fluids, etc. are all imageable at this level. MRI is often presented as a new and superior imaging method, but it is important to realize that MR is limited to soft, hydrated tissues. CT remains the only imaging modality capable of simultaneous, high resolution imaging of the full structural gamut of solids through air. For marine science, this combined capacity for broad data ranges, high resolution, and rapid imaging is critically important.

Equally important, CT offers the advantage of matrix data for both the attenuations and reformatted images that are readily exportable to virtually any platform and are compatible with most modeling efforts. The attenuation data can also be sub-divided or segmented to provide powerful, dramatic three-dimensional visualizations of specific internal structures. CT therefore has much to offer any research dependent on knowledge of internal structure and structural relationships. For marine research in particular, in a very literal sense, it offers us the ability to image the "anatomy" of any marine system at a micro to macro scale.

## **WORK COMPLETED**

A Siemens spiral CT Emotion scanner unit (Model 3810400) was purchased after reviewing competitive bids from Siemens, Inc. for \$530,952 using all of this grant's funds and the balance from ONR DURIP grant N000140110499. This purchase price represents a 26% discount on the equipment and a waiver of installation and applications training fees for an approximate total 50% discounted cost over list for equipment with the required installation. Conventional clinical scanners of this grade with installation cost approximately \$1.2 million. This pricing reflects a combination of unusual circumstances that provides an exceptional reduction in costs to the

research community. Siemens has provided a full maintenance contract and tube insurance for the first year at no additional cost. The equipment currently installed is a new, 6<sup>th</sup> generation helical scanner with resolutions and scanning capacities as described in the preceding paragraphs. The equipment has an extra power capacity that allows rapid, and therefore *in vivo*, imaging of even moderate sized toothed whales (450 lbs). It also uses the newest low dose technology, which reduces concerns for exposures to live animals and enhances the tube life. Because the system is Windows-based, it is projected that this fundamental scanner design, with periodic software upgrades will continue in use for 7 to 10 years at a minimum.

Installation and safe use of the scanner required major modification of existing space. WHOI, in order to assure maximum safety and accessibility, provided \$500,000 from its resources which it intends to recover through depreciation, to build housing for the scanner and all required control rooms according to Siemens specifications.

Training on its use and on in-line reconstruction and measurement software was completed by J. Arruda (resident CT technologist, WHOI) and D. Ketten (PI). In addition, Dr. Ketten visited the Siemens factory in Germany to discuss program improvements and scanner upgrades for the following year. Dr. Ketten also completed and received CME accreditation in Neuroradiology in a course conducted by AFIP at Walter Reed Medical Center.

## RESULTS

Work using this scanner has been underway for approximately 8 months. Specimens that have been scanned include over 6 species of toothed whale, 2 species of pinnipeds, 3 species of turtles, 5 species of fish, crustaceans, corals, bivalves, alligators, hippos, emu, tiger, and 2 species of primates. Over 80 specimens from 10 different PI's have been examined.

Collaborative and contract work to date utilizing this scanner included the following PIs and projects:

*Anne Cohen* (WHOI): Coral reef variations with climate

*Peggy Edds-Walton* (Parnley Research Institute): Otolith Mineralization and Diet; Otolith structure and hearing in fishes

*Frank Fish* (Westchester Univ.): Imaging of control surfaces of dolphins

*Tecumseh Fitch* (Harvard University): Comparative anatomy of sound production in land and aquatic mammals

*D.R. Ketten* (WHOI): Cetacean, pinniped, and turtle hearing models; Blast impacts, Head FEM models, Ear pathology and trauma

*Andone Lavery and Tim Stanton* (WHOI): Acoustic scattering models of fish and crustaceans

*J.B. Nadol* (Harvard Medical School): 3D imaging of cochlear pathologies

*NOAA Fisheries*: Five Cause of Death case studies for turtles and cetaceans

*Arthur Popper* (Univ. of Maryland): Fish swim bladder and otolith anatomy

*Margaret Skinner* (Washington Univ. Med. School): Cochlear implant position and performance

*Jacqueline Webb* (Villanova University): Chaetodontid fish systematics and swim bladder morphology

## IMPACT/APPLICATIONS

In the near term, we expect projects underway to produce significant data related to acoustic impacts, blast effects, cetacean locomotion, reef health and global warming, and acoustic scattering models. Because of the current success and enhancement of a broad base of research for which this imaging facility is already providing support, we expect to expand to even more fields of research in the next year with the advent of an even larger capacity core machine. Further, because we have close ties with the Harvard Surgical Planning Laboratory and we have more leeway to explore new imaging strategies than do most clinical centers, we expect to make substantial contributions to biomedical imaging research as well. Consequently, this facility and its work are relevant to the Medical Science and Technology as well as to the Marine Mammal and Acoustical Oceanography Divisions of ONR.

## TRANSITIONS

The majority of projects employing this facility to date are funded through ONR and therefore the transition of results is project specific (see Results section and Publications below).

## RELATED PROJECTS

The CT Scanner presently in operation at WHOI was purchased with this grant in conjunction with ONR DURIP grant N000140110499.

## PUBLICATIONS (acknowledging ONR support)

de Muizon, C., D.P. Domning, and D.R. Ketten (2002) *Odobenocetops peruvianus*, the walrus-convergent delphinoid from the lower Pliocene of Peru. (in press, *Smithsonian Cont. Paleobiol.*)

Fish, F. E. and Ketten, D.R (2003) Examination of Three-Dimensional Geometry of Cetacean Flukes Using CT-Scans. SCIB.

Ketten, D.R. (2001) Whales, Ship Strikes, and Sound: What We Know and What We Need to Know, *Invited paper*, European Cetacean Society, Rome, Italy.

Ketten, D.R. (2002) Anthropogenic effects of Ocean Noise: Known and potential causes of hearing loss in Marine Mammals *Invited paper*, Deutsche Forschungsgemeinschaft, Workshop, Impact of Acoustics on Marine Organisms, Berlin.

Ketten, D.R. (2002) Bahamas Beaked Whales, *Invited paper*, Annual Meeting of NOAA Fisheries Working Group on Marine Mammal Unusual Mortality Events.

Ketten, D.R. (2002) Marine Mammal Hearing and Evidence for Hearing Loss, *Invited paper*, IAGC Workshop on Seismic Exploration.

Ketten, D.R. (2002) Ocean noise as a stressor of marine mammals, *Invited paper*, Florida Marine Mammal Health Conference, Gainesville, Fla.

Ketten, D. R., Cramer, S., O'Malley, J., Fischer, I., Reidenberg, J., Naples, V., McCall, S., Craig, J., Tussing, R., Rye, K., Lewis, W., Potter, C., Ososky, J. and Merigo, C. (2001) Experimental Measures of Blast Trauma in Marine Mammals, Thirteenth Biennial Conference on the Biology of Marine Mammals

Ketten, D. R., O'Malley, J., Mead, J., Sandberg, G., and McCall, S. (2001) Beaked Whale Auditory Systems: Structure, Specializations, and Correlates of Trauma, *Invited paper*, Thirteenth Biennial Conference on the Biology of Marine Mammals

Ketten, D. R., O'Malley, J., Moore, P. W. B., Ridgway, S., and Merigo, C. (2001) Aging, injury, disease, and noise in marine mammal ears, Acoustical Society of America.

Marsh, S.E., Fischer, I., Arruda, J. and Ketten, D.R. (2001) Morphometric analyses of hearing in two families of pinnipeds, Acoustical Society of America.

Nadol, J.B., Jr., J.Y. Shiao, B.J. Burgess, D.R. Ketten, D.K. Eddington, B.J. Gantz, I. Kos, P. Montandon, N.J. Coker, J.T. Roland, Jr., and J.K. Shallop (2001) Histopathology of Cochlear Implants in humans. *Annals of Otology, Rhinology, and Laryngology*. 110(9):883-91.

Reidenberg, J.S., D.R. Ketten, S. Marquez, and J.T. Laitman (2001) Is there a clinical price in deviating from the norm? An investigation of structural and functional asymmetry in the upper respiratory tract. Assoc. for Resch. in Otolaryngology.

Skinner, M.W., L.T. Cohen, D.R. Ketten, L.K. Holden, E. Muka, B. Whiting, F.J. Wippold, K.T. Bae, P.G. Smith, G.A. Gates, J.G. Neely, G.R. Kletzker, B. Brunnsden, and R. Havener (2002) 2D Radiograph and CT Derived Estimates of the Position of Cochlear Implant Electrodes in Nucleus-22 Recipients. (submitted, *JARO*)

Skinner, M.W., D.R. Ketten, L.K. Holden, P.G. Smith, G.A. Gates, J.G. Neely, B. Brunnsden, and B. Blocker (2002) CT Derived Estimation of Cochlear Morphology and Electrode Array Position in Relation to Word Recognition in Nucleus-22 Recipients. (in press, *JARO*)

Skinner, M.W., D.R. Ketten, L.K. Holden, B.R. Whiting, K.T. Bae, L.T. Cohen, J.G. Neely, G.A. Gates, P.G. Smith, G.R. Kletzker (2002) Is there a relation between speech recognition and the position of cochlear implant electrodes in the inner ear? *Seminars in Hearing*. (in press, *JARO*)

Webb, J.F., Smith, W.L. and Ketten, D.R. (2001) The Laterophysic Connection, A Unique Swim Bladder-Lateral Line Connection in Butterflyfishes: An Evolutionary Novelty with Implications for Sensory Function, Sixth International Congress of Vertebrate Morphology, Jena, Germany.

Webb, J.F., Smith, W.L., Trikas, T. and Ketten, D.R. (2002) The laterophysic connection: A novel specialization thought to enhance sound pressure sensitivity in butterflyfishes (Chaetodontidae, Chaetodon) Invited paper, Acoustical Society of America.

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**13. SUPPLEMENTARY NOTES****14. ABSTRACT**

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